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A mechanistic model of runoff-associated fecal coliform fate and transport through a coastal lagoon

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Abstract

Fecal coliform (FC) contamination in coastal waters is an ongoing public health problem worldwide. Coastal wetlands and lagoons are typically expected to protect coastal waters by attenuating watershed pollutants including FC bacteria. However, new evidence suggests that coastal lagoons or marshes can also be a source of high indicator organism concentrations in coastal waters. We asked for a Mediterranean-type climate, what is the fate of runoff-associated FC through a coastal lagoon? To address this question, we developed a mass balance-based, mechanistic model of FC concentration through a coastal lagoon and simulated, for summer and winter conditions, FC within the lagoon water column, lagoon sediments, and in the ocean water just downstream of the lagoon mouth. Our model accounts for advective flow and dispersion, decay and sedimentation and resuspension of FC-laden sediments during high flow, erosional conditions. Under low flow conditions that occur in the summer, net FC decay and FC storage in lagoon sediments are predicted. Under high flow conditions that occur in the winter, FC-laden sediments are predicted to erode, resuspend and flow out of the lagoon where they elevate FC concentrations in the coastal ocean. For both seasonal conditions, the predicted water column FC concentrations were within an order of magnitude of field measurements for a reference site in southern California. Our results suggest that there are seasonally varying roles for coastal lagoons in mediating FC contamination to coastal waters.

Keywords: Fecal coliform; Watershed; Coastal; Water quality; Sediment; Non-point source; Lagoon; Estuary

1. Introduction

Fecal coliform (FC) pollution in coastal waters is a high priority problem worldwide that has not been completely ameliorated by secondary wastewater treatment [1]. Still problematic to coastal ocean water quality are non-point FC sources such as stormwater runoff, septic systems, sanitary sewers and wildlife [2–6]. Because non-point sources are many and varied, identifying and eliminating them is a complex task. However, it is possible to mitigate non-point FC pollution through source delineation, field study, system analysis and field management [7]. Mathematical, process-based system models may be an important tool for hypothesis-building in the search for significant yet diffuse sources of fecal pollution. In this study, we developed a mathematical model to address the fate of creek-associated FC on downstream ocean water quality.

Many coastal streams in southern California do not discharge either directly to the coastal ocean or into a large bay. Instead, they discharge to a smaller coastal estuary or lagoon where waters may reside long enough for FC to settle, accumulate, and potentially multiply. Although not completely understood, lagoon or marsh processes may determine to what degree upstream non-point pollution in the watershed measurably impacts

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Nomenclature

A	lagoon sediment surface area (m^2)
C	FC concentration in lagoon water (MPN/m^3)
C_d	empirical drag coefficient, dimensionless
C_l	empirical dispersion parameter, dimensionless
C_o	FC concentration in ocean water (MPN/m^3)
C_{ob}	FC background concentration in ocean water (MPN/m^3)
C_{out}	FC concentration in the lagoon water at the outlet or $C_{x\max,\,t}$ (MPN/m^3)
C_s	FC concentration in sediment (MPN/kg)
d	mixing depth of sediment (m)
f	fraction of FC in water column associated with suspended sediments, dimensionless
E_t	turbulent dispersion coefficient (m^2/s)
E_s	ocean turbulent diffusion coefficient parallel to the shoreline (m^2/s)
E_y	ocean turbulent diffusion coefficient perpendicular to shoreline (m^2/s)
g	gravitational acceleration (m/s^2)
H	lagoon channel depth (m)
k	FC first-order overall removal constant in lagoon water (1/s)
k_d	FC first-order death constant in lagoon water (1/s)
k_o	FC first-order death constant in ocean water (1/s)
Q	lagoon water flow rate (m^3/s)
R_t	lagoon sediment resuspension rate, (kg/m^2 s)
S_l	lagoon channel slope, dimensionless
t	time (s)
T	water temperature (K)
TSS	average total suspended solids concentration in the water column (kg/m^3)
u^*	shear velocity (m/s)
u_t	velocity (m/s)
u_w	wind speed (m/s)
U_s	ocean shoreline current velocity (m/s)
v_s	particle settling velocity (m/s)
v_b	lagoon sediment burial velocity (m/s)
w	lagoon average channel width (m)
x	distance (m)
x_s	distance from the lagoon mouth, parallel to shoreline (m)
y	width of ocean subunits, perpendicular to shoreline (m)

Greek symbols

Δt	time step size
Δs	spatial step size
ρ_a	air density (kg/m^3)
ρ_s	sediment wet bulk density (kg/m^3)
ρ_w	water density (kg/m^3)
τ	shear stress at the sediment surface (N/m^2)
τ_c	critical shear stress for sediment resuspension (N/m^2)

Subscripts

x	distance
t	time
s	sediment
max	maximum

Abbreviations

FC	fecal coliform
MPN	most probable number

coastal water quality. A recent study of a southern California marsh suggests that the marsh is a source of FC loading to the coastal ocean [8]. This is in contrast to the conventional wisdom that marshes and lagoons primarily filter pollutants from creek water and thereby reduce their discharge to the coastal ocean. Particularly because two contrasting roles are assigned to lagoons and marshes, it is important to gain an understanding of what happens to FC in lagoons. Urban runoff can be a significant source of fecal contamination to coastal waters, but it is important to know how lagoon processes may mediate the impact of upstream urbanization on downstream coastal water quality.

One way in which lagoons or coastal estuaries could impact FC loadings to the ocean is through storage in sediment and seasonal release. Lagoons have large reserves of consolidated sediments due to intermediate concentrations of salts and low velocities, which together encourage the aggregation and sedimentation of suspended particles. Importantly, sediments often contain high concentrations of fecal indicator bacteria as compared to the overlying water column [9,10]. Therefore, the physical characteristics, coupled with the intermediate location between freshwater and ocean water, suggest that lagoons could either protect the coastal ocean from watershed processes or, under episodic high (erosional) flow conditions, release contaminated sediments to the coastal ocean.

Our overall objective in this work was to mathematically model the physical processes in a coastal lagoon that affect FC originating from urban creek runoff-associated and dry weather inflow. The purpose of creating such a model is that it provides a basis for thinking about and understanding the seasonally varying connectivity between creek water quality and downstream ocean water quality. The model is also a useful framework with which to design and guide field studies of the lagoon, an important intermediate environment between California coastal creeks and the ocean. While our simulations are subject to necessary assumptions with some need for field validation, the simulation results and sensitivity analyses provide useful insight into when specific physical processes are most important. Our results also are useful for assessing the relative importance of model assumptions and where calibration efforts should be focused.

2. Field site description

Our modeling approach is mechanistic and generalizable, but the model itself contains model parameter values that are site and season-specific. To test the efficacy of the model as a possible management tool, we compared the output of our model simulations to actual field measurements of FC concentrations and chose values of site-specific parameters to match the field site. We selected our simulation conditions to represent the Arroyo Burro (AB) lagoon in Santa Barbara, CA (Fig. 1). As shown in Fig. 1, the AB lagoon is situated between the mouth of AB creek and Hendry's Beach, the latter being a popular bathing and surfing area where coastal water frequently exceeds California recreational FC standards (http://www.sbcphd.org/ehs/ocean.htm). The AB watershed drains approximately $6\,km^2$ with land uses shown in Fig. 1. Historically, FC concentrations in the ocean on the west side of the lagoon mouth are background while concentrations on the east side may be a result of fate and transport processes from the AB watershed and lagoon. We measured the lagoon channel dimensions and water flow rate for two seasonal conditions (Table 1). We also measured the mixing zone geometry for the ocean at Hendry's Beach (Table 2).

The AB lagoon is only periodically tidally influenced, similarly to other southern California lagoons [11]. In our model development and simulations, we considered two non-tidal scenarios—dry season base flow and the wettest storm of the winter. These two scenarios were selected because, respectively, they represent the sustained scenario during peak periods of beach recreation and the acute hydraulic event (berm erosion) that initiates the sustained base flow conditions. Over the course of every summer, a sand berm gradually builds up at the outlet of the lagoon and the lagoon essentially closes off by early fall. Salinity and water surface elevation measurements that we made in the lagoon in August and September 1999 confirm that the lagoon is not tidally influenced during this later stage of the dry season (data not shown). The berm, a typical beachscape formed along southern California coastlines, is intact in the late summer and into the fall season but is breached in the winter when storm flows are high. After the berm is breached, the abundant freshwater discharge will initially prevent tidal influx of ocean water to the lagoon. During spring and early summer, the berm slowly builds again and hydraulic connectivity between the ocean and the lagoon moves from surface (tidal) flow to subsurface flow beneath the berm.

The influence of the AB watershed and lagoon discharge on ocean water quality at Hendry's Beach is evidenced by a field study conducted for Santa Barbara County [12]. FC concentrations in lower AB creek and in the AB lagoon for February 2, 1999 were reported as 4E6 and 8E6 MPN/m^3, respectively; California's single sample standard for FC in recreational waters is 4E6 MPN/m^3. On March 26, 1999, when the lagoon discharge was as high as $0.79\,m^3/s$, FC concentrations in the ocean at the lagoon mouth were recorded at 1E7 MPN/m^3, and decreased 90% over a distance of 366 m eastward (down gradient) along the coast. Background FC concentrations (west of the lagoon mouth) were approximately 1E5 to 2E5 MPN/m^3. This and other data from the 1999 report [12] are compared to the output of our model simulations for the two selected seasonal conditions.

3. Mathematical modeling

The overall focus of our modeling effort is to mathematically describe the fate of FC associated with runoff as it migrates through a coastal lagoon. While there are many potential sources of FC in the lagoon (e.g. birds, runoff, subsurface flow and amplification on decaying vegetation as per [8]), we have focused our attention on one source (urban runoff) that is commonly suspected to be a primary contributor to non-point source FC contamination in coastal waters. We emphasize the lagoon as our modeled system because it receives all watershed discharge, is between the watershed and coastal ocean and thus has the potential to mediate the effects of upstream processes on the coastal ocean. Yet the lagoon appears to function hydrodynamically independently of either the upstream creek or coastal ocean. The elements of our model include the time-variant lagoon FC concentration which has embedded in it a time-variant term for sediment FC concentration. We therefore use a separate model of lagoon sediment FC that accounts for both the storage of FC in sediments and the dynamics of FC-contaminated sediment during seasonal or episodic erosion. Lastly we introduce a third model that simulates the impact of lagoon water FC loading on the ocean water FC concentration. The output of the latter model are compared to field data for the Hendry's Beach site at the terminus of the AB watershed.

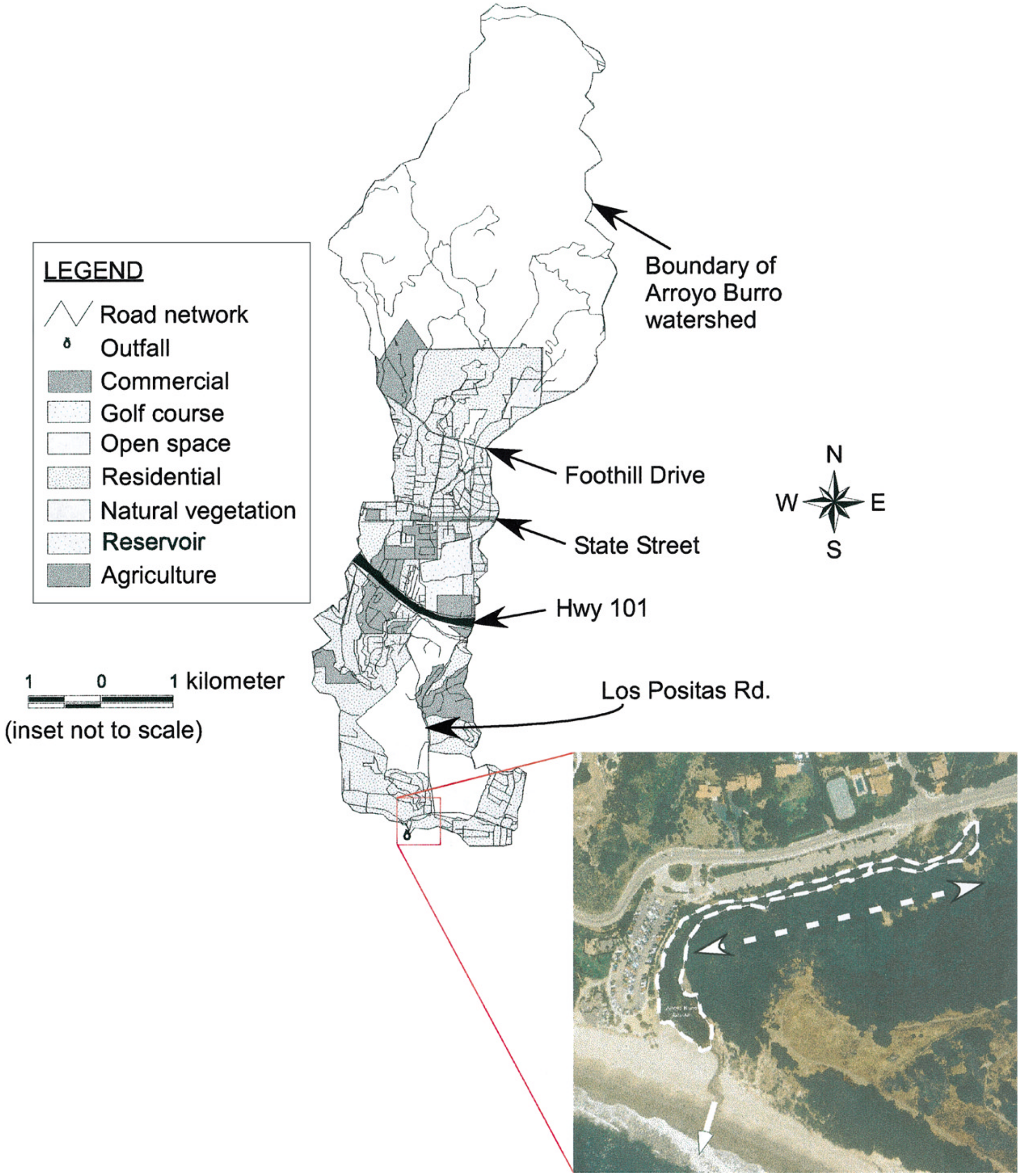

Fig. 1. Map of the reference site for this study: Arroyo Burro watershed, lagoon and Hendry's Beach in Santa Barbara, California. The expanded photographic inset shows the outline (white, dotted) of the AB lagoon. The dotted line to the right of the lagoon indicates the longitudinal axis of the lagoon and the discharge to the beach (large arrow).

Table 1
Lagoon model input parameters and values

Name	Summer value	Winter value	Units	Description
t_{max}	259,200	129,600	s	Run time
dt	1440	150	s	Timestep
x_{max}	412	412	m	Lagoon length (from Cliff Dr. bridge)
dx	3	69	m	Spatial step size (longitudinal direction)
w	14	13	m	Average width
H	0.69	0.81	m	Average depth
Q	1.7×10^{-2}	0.3–4.6	m^3/s	Flowrate
E_t	0.003	1.02	m^2/s	Longitudinal turbulent dispersion coefficient
f	0.90	0.90	—	Fraction FC cells associated w/ suspended sediments
d	0.05	0.05	m	Depth of active surficial sediment layer
ρ_s	1400	1400	kg/m^3	Sediment wet bulk density
v_s	4.17E-6	0	m/s	Average settling velocity of fine-grain sediments
TSS	0.3	1.5	kg/m^3	Total suspended solids concentration
k_d	1.74E-5	8.68E-6	s^{-1}	FC first-order (freshwater) death rate coefficient
R_t	0	5.49 E-4	$kg/m^2 s$	Sediment resuspension rate
u	0.0017	0.31	m/s	Lagoon water velocity

Table 2
Ocean model input parameters and values

Name	Summer value	Winter value	Units	Description
t_{max}	259,200	129,600	s	Run time
dt	18	18	s	Timestep
x_{max}	150	150	m	Simulation distance (east of mouth, along shoreline)
dx	6	6	m	Spatial step size
w	9	9	m	Average width of mixing zone
H	0.5	0.5	m	Average depth of mixing zone
U_s	0.25	0.25	m/s	Alongshore current velocity
E_s	1	1	m^2/s	Horizontal turbulent dispersion coefficient
k_o	1.74E-5	1.16E-5	s^{-1}	FC first-order (marine water) death rate coefficient
C_{ob}	2E5	2E5	MPN/m^3	Background FC concentration

4. FC concentration in lagoon water

Our approach is mechanistic: we use the advection-dispersion equation and account for removal (first-order settling and death), time-variant sediment storage, and sediment resuspension. Several previous models of FC fate and transport are of the multivariate [13–15]) or distance-decay regression [16] types. Deterministic approaches have been used to model FC transport in streams and lakes [17–19]. Also, a loss term for bacterial death has been included in previous models [17,13]. Our modeling approach is different in that it also accounts for particle-associated FC deposition and resuspension. We modeled the latter two processes because up to 90% of FC in streams and bays are associated with suspended sediments [17,20–23] and the overall trend from a number of studies shows a significant correlation between FC concentrations in sediment and overlying water [24,25].

The lagoon water model was developed around a control volume with processes depicted in Fig. 2. The resulting partial differential equation describing time-variant FC concentration in the lagoon waters is

$$\frac{\delta C}{\delta t} = -u_t \frac{\delta C}{\delta x} + E_t \frac{\delta^2 C}{\delta x^2} - kC_{x,t} + R_t \frac{C_{s,t}}{H}. \quad (1)$$

In Eq. (1), the terms on the right-hand side describe advective flow, turbulent dispersion, removal and resuspension. The lagoon water velocity, u_t, which changes for the summer and winter conditions, was calculated using measured values of depth (H), flow rate (Q) and width (w) for AB lagoon (Table 1). Explanations of E_t, k and R_t values are provided in the following paragraphs.

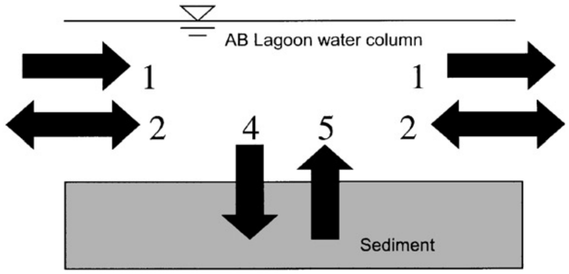

Fig. 2. Schematic of a lagoon water column and sediment control volumes depicting relevant transport processes. The processes are: (1) advection, (2) dispersion, (3) die-off (not shown), (4) decay and settling and (5) resuspension. Not shown is the additional process of surface sediments depositing into an erodable sediment layer.

4.1. Turbulent dispersion, E_t

Turbulent dispersion coefficients vary with flow rate. Under low flow (lake-like) conditions in a lagoon, wind-induced shear stresses can cause mixing. During turbulent (river-like) flow conditions, velocity gradient-induced shear stresses control mixing. Therefore, two different empirical relationships are evaluated for estimating E_t for summer and winter conditions. First, Fischer et al. [26] proposed the following relationship for wind-induced dispersion.

$$E_t = C_1 u^* H \quad \text{and} \quad u^* = u_w \left[\frac{C_d \rho_a}{\rho_w}\right]^{0.5}. \tag{2}$$

Fischer et al. [26] also proposed the following relationship for flow-induced (longitudinal) dispersion, applicable for the lagoon during storm flow conditions:

$$E_t = 0.011 \frac{u^2 w^2}{H u^*} \quad \text{and} \quad u^* = \sqrt{gHS_l}. \tag{3}$$

In actuality, the AB lagoon is highly protected from wind shears due to its high, sharp banks and thick surrounding vegetation. Therefore, Eq. (2) is likely to over-predict E_t even for small wind velocities. By way of explanation, for average winds of 5 m/s (using coefficient values determined for Onondaga Lake [17]), an E_t of $17\,m^2/s$ is calculated. However, if we extrapolate from a plot of lake dispersion coefficients versus various length scales [27] using the summer-condition width of the lagoon (Table 1), then E_t is approximately $0.01\,m^2/s$. For the summer condition we selected an E_t value to meet two stability criteria that apply to both the lagoon and ocean advection-dispersion equations. The first is the Peclet condition, which states that the modeling spatial step-size times velocity divided by dispersion must be less than 2. The second is the Courant condition [28], requiring velocity to be less than the modeling spatial step-size divided by the time-step. Because the flow rates, lagoon channel cross-section, and thus velocities, are known, E_t is only constrained by these two mathematical conditions. The resulting value of E_t for the summer conditions is $0.003\,m^2/s$ (Table 1).

We used Eq. (3) to calculate E_t for the winter storm flow condition. For a peak winter storm flow event of $4.6\,m^3/s$ (Table 1) and a lagoon slope of 8 m/1350 m (determined from the US Geological Survey topographic map of AB lagoon), an E_t value of $1.02\,m^2/s$ is estimated. This is an acceptable value when compared to published values [27] assuming winter conditions and AB lagoon geometry. It should be noted for both the winter and summer conditions that, within each condition, we assumed a constant cross-sectional area for the lagoon over the length of the lagoon. Based upon our field observations, this is a reasonable first assumption, and the theoretical dependence of E_t on cross-sectional area collapses into values of E_t independent of x (Eq. (1)).

4.2. FC removal kinetics

The first-order removal coefficient (k, Eq. (1)) is an overall coefficient representing combined death and settling:

$$k = k_d + \frac{V_s}{H} f. \tag{4}$$

The death coefficient (k_d) for FC in water correlates with a number of biological and physicochemical factors including clay concentration [29], predation/competition [30–32], temperature, salinity, and solar irradiance [17,33], and turbidity, sewage content (i.e. nutrients) and degree of mixing [34]. Empirical correlations between k_d and important aquatic environmental factors such as irradiance, light attenuation depth and temperature are available [17,33]. However these correlations were derived for freshwater and are less applicable to the turbid, brackish waters of coastal lagoons. For our simulations, we compiled a table of published values for k_d (Table 3) from which we selected a representative k_d value. Gersberg et al. [11] measured a k_d value of approximately $1.9E\text{-}5\,s^{-1}$ for a tidally influenced southern California coastal lagoon water during summer conditions using in situ dialysis tube experiments. Due to the climatic similarity between study sites, we assumed that the AB lagoon k_d values are very similar to the in situ values reported by Gersberg et al. [11].

The overall removal coefficient, k, used in our simulations is calculated from Eq. (4) using parameter values given in Tables 1 and 2. We calculated a representative particle settling velocity, v_s, using Stoke's Law [41] and then computed an overall removal coefficient for the two seasonal flow regimes using Eq. (4). We evaluated the sensitivity of our model results to variations in k_d. As explained in the sediment model

Table 3
A summary of published FC death coefficients relevant to lagoon systems

System; measurement method	k_d, $s^{-1} \times 10^5$	Reference
Freshwater; dialysis tubes[a]	1.37–3.24	Auer and Niehaus [17]
Marine and freshwater; laboratory	0.65–2.47	Gonzalez [36]
River impoundment; tracer	11.1	Gannon [20]
Stream; in situ dialysis chambers	1.15 (293 K)–0.56 (288 K)	McFeters and Stuart [37]
California coastal lagoon; in situ dialysis tubes	1.85	Gersberg et al. [11]
Freshwater; laboratory in the dark	0.24 (288 K)–0.59 (293 K)	Evison [38]
Saltwater; laboratory in the dark	0.65 (288 K)–0.59 (293 K)	Evison [38]
River; laboratory incubation in the dark	1.39 (288 K)–1.85 (293 K)	Flint [30]
Constructed wetlands	1.89	Khatiwada and Polprasert [39]
High rate algal pond with synthetic sewage	0.41–2.71	Fallowfield et al. [40]

[a] Measured for water depths similar to AB lagoon, this study.

presentation, we assumed that for bacteria in sediments $k_d = 0$.

4.3. Sediment resuspension

Estuarine sediments contain concentrations of indicator organisms that are 1–3 orders of magnitude greater than those in the overlying water [24], and 3–4 orders of magnitude greater in storm drain sediments [42]. Storm events and/or tidal flushing events that result in the resuspension of lagoon sediments can increase the flux of fecal contamination to the coast. Therefore it is important to be able to predict resuspension as a function of lagoon flow conditions.

In sediment, there is a critical shear stress, τ_c, below which resuspension, and above which sedimentation, is not likely. The Shield's Curve with theoretical [43] and measured [44] versions provides the relationship between τ_c and grain diameter. For the initiation of grain movement, the shear stress at the sediment surface, τ, is such that $\tau > \tau_c$. When $\tau < \tau_c$, deposition is the dominant sediment transport process. To determine which process dominates for our simulations, we used the following velocity-shear stress relationship [45]:

$$\tau = 3 \times 10^{-3}\, u_t^2. \tag{5}$$

During base flow conditions the average AB lagoon velocity is approximately 1.7E-3 m/s, resulting in a bed shear stress (Eq. (5)) of $8.7 \times 10^{-6}\,\mathrm{N/m^2}$. During winter storm flow conditions, the lagoon water velocity is approximately 0.31 m/s and the calculated shear stress is $0.29\,\mathrm{N/m^2}$. By Cardenas et al. [45] a τ_c of approximately $0.1\,\mathrm{N/m^2}$ retains consolidated river sediment, whereas Lee et al. [46] suggests a value of about $0.02\,\mathrm{N/m^2}$ for fine-grained consolidated bay sediments. Based upon lab erosion data for 10^{-6} m quartz (bulk density $1500\,\mathrm{kg/m^3}$), Roberts et al. [44] recommends a critical shear stress of $0.1\,\mathrm{N/m^2}$. Regardless of which τ_c is applied, during summer conditions sedimentation clearly dominates erosion in the AB lagoon. Similarly, Arfi and Bouvy [47] found that sedimentation dominated for a shallow tropical lagoon in which mixing was only by winds that were similarly calm to those that occur within AB during the summer. Conversely, during winter storm flow the AB lagoon is operating under conditions that strongly favor sediment resuspension. Thus, our simulation of lagoon FC (Eq. (1)) omits the resuspension term for the summer, but the winter model does include a term for resuspension (Table 1).

Resuspension and sedimentation are combined into a "net resuspension" term, R_t, because the two processes occur simultaneously for fine-grained sediments. Our estimate for resuspension, R_t, was made by assuming the sediment erosion rate and the depth of erodable sediment. Net resuspension was set at a rate in which 0.0508 m would be lost over the entire sediment bed, uniformly in time, over the course of the simulated storm event (129,600 s). This corresponds to a rate of 3.92E-7 m/s, a value within the range expected based upon inspection of erosion rate versus bulk density lab data for (fine-grained) Detroit River sediment cores [48] at the maximum shear stresses experienced within the lagoon during this event. Assuming a sediment bulk density of $1400\,\mathrm{kg/m^3}$ the resulting estimate of R_t is 5.49 E-4 $\mathrm{kg/m^2\,s}$ (Table 1). We test the model sensitivity to R_t because its value is perhaps the most uncertain of all the parameters in our model.

5. Storage in lagoon sediment

Another mass balance equation is required to model the storage of FC in the sediment ($C_{s,t}$ in Eq. (1)). Our concept of the sedimentation process, as depicted in Fig. 2, is that the fraction of FC that are particle-associated become concentrated in the sediment, beginning at the sediment-water interface. We assume that all particle-associated FC enter the sediment via a Stoke's

Law process where they become immediately concentrated in proportion to the ratio of sediment bulk density to TSS in the water column. Sediment FC concentrations are assumed to be constant with depth.

We assume that sediment accumulation is equal to sedimentation minus "burial". The process of "burial" is a model construction. A constant-volume control volume is assumed which means that the control volume ascends relative to a fixed reference frame as sediment accumulates. A "burial velocity" is utilized by the storage model to account for this modeling artifact. The burial velocity is set equal to the settling velocity times the ratio of TSS to wet bulk density, thereby accounting for the change in solids concentration when going from suspended to bed solids.

Advective and dispersive flow of FC are neglected because the bacteria in the sediment are assumed to be mainly attached and non-motile. We also exclude a bacterial decay loss term from our sediment storage model because the FC population size is assumed to be relatively stable in sediments. This latter assumption is supported by numerous field studies that not only show higher concentrations of FC in sediments versus overlying water [49], but also FC and pathogen survival periods ranging from days to months [2,31,42,50,51]. The resulting ordinary differential equation is

$$\rho_s A d \frac{\mathrm{d}C_s}{\mathrm{d}t} = v_s A f \frac{\rho_s}{\mathrm{TSS}} C - v_b A \rho_s C_{s,t}. \tag{6}$$

Eq. (6) is used to calculate the time-variant concentration of sediment FC which is required to solve Eq. (1) and thus compute net effluent FC concentrations in the lagoon water.

FC cells are largely associated with fine-grained sediments that will be removed from the water column by settling if the hydraulic detention time in the lagoon is sufficient. Applying Stoke's Law [41] to clay ($\rho_s = 2300\,\mathrm{kg/m^3}$, d= 7E-7 m) and fine silt particles ($\rho_s = 2650\,\mathrm{kg/m^3}$, d= 1E-5 m), we calculate settling velocities of 2.66E-7 and 6.42E-5 m/s, respectively. For an average AB lagoon depth of approximately 0.75 m, only silts will be removed through the lagoon. We used the average of the two settling velocities, i.e. 4.17E-6 m/s as a first approximation for v_s in our simulation. By comparison, Auer et al. [17] determined the limnetic settling rates of a number of different particle classes, and found settling rates of 1.16E-5 and 3.47E-5 m/s for the two classes with which 90% of the FC were associated (4.5E-7 to 1E-6 m clays and 6E-6 to 1E-5 m silts, respectively). The FC concentration-weighted average settling velocity used by Auer et al. [17] was 1.6E-5 m/s. In the coastal pathogen transport model developed by Connolly et al. [52] an average settling speed of 7.98E-5 m/s was used. In Lick et al. [53] settling speeds in lab flocculation experiments were measured from 1.04E-5 to 3.01E-5 m/s for fine-grained sediment flocs of 1E-5 m diameter (equivalent to that of fine silts) at varying shears. These values correspond roughly with those rates predicted via Stoke's Law above and differences can be explained by particle densities, shape factors, and effective diameters.

6. Coastal ocean FC transport

The lagoon discharges into the coastal zone, mixes with the ocean and the mixture moves down current. Coastal mixing and down current transport processes are important to consider because FC levels in the surf zone, not lagoon FC levels, are of main concern to coastal water quality managers. A simple, yet applicable ocean transport equation considers 1D advection-dispersion plus reaction as follows:

$$\frac{\delta C_o}{\delta t} = -U_s \frac{\delta C_o}{\delta x} + E_s \frac{\delta^2 C_o}{\delta x^2} - k_o C_o - \frac{E_s}{y} \frac{(C_o - C_{ob})}{y/2}. \tag{7}$$

A dispersive term in the y-direction (E_s/y) is included in Eq. (7) to account for offshore subunit losses, where FC concentrations are assumed to be equal to a constant background level (C_{ob}). The effects of wave breaking, wave runup-rundown and swashing, wave interaction with shallow bottom topography, and wind-induced shears on mixing are represented by this single dispersion term. For the ocean model (Eq. (7)), we assumed E_s (Table 2) to be less than the turbulent dispersion in the lagoon during winter storm flow conditions but higher than values reported for waters further offshore in the Santa Barbara Channel [54].

The boundary conditions of the ocean transport model assume that the lagoon is the source of FC, and that complete and instantaneous mixing occurs at the lagoon mouth:

$$C_o(s = 0, t) = C_{ob} + \frac{\Delta t Q C_{out}}{\Delta s y H_0}. \tag{8}$$

The numerator of the last term in Eq. (8) represents the FC concentration entering the ocean from the lagoon mouth during one model time step, while the denominator represents the volume of the ocean subunit.

7. Simulation conditions

Tables 1 and 2 list the model input values for the lagoon and ocean, summer and winter simulations. We measured water velocity and lagoon channel dimensions directly in the field. Tables 4 and 5 provide sensitivity analysis parameters for the lagoon under the two seasonal conditions simulated in this study. The second column in each Tables 4 and 5 displays the original parameter values used by the model simulations previously discussed, while the remaining columns

Table 4
Summer model sensitivity analysis input parameter values

Parameter	Original	Low decay	Short-circuiting	Pulse input	High decay
k_d (s^{-1})	1.74E-5	1.16E-5	1.74E-5	1.74E-5	1.74E-5
v_s (m/s)	4.17E-6	4.17E-6	4.17E-6	4.17E-6	1.60E-5
f	0.90	0.75	0.90	0.90	0.90
Bndry Cond. (MPN/m^3)	4E6	4E6	4E6	4E7[a]	4E6
u_t (m/s)	1.73E-3	1.73E-3	2.59E-3[b]	1.73E-3	1.73E-3

[a] FC concentrations at lagoon entrance for pulse input scenario begin at 4E7 for 14400 s, then fall back to 4E6 for remainder of summer simulation.
[b] Lagoon velocity for short-circuiting scenario is 50% greater, i.e. $u = 1.5Q/A_c$.

Table 5
Winter model sensitivity analysis input parameter values

Parameter	Original	High resusp.	Low decay	High decay	Low resusp.
R (kg/m^2 s)	5.49E-4	1.10E-3	5.49E-4	5.49E-4	2.75E-4
k_d (s^{-1})	8.68E-6	8.68E-6	6.94E-6	1.39E-5	8.68E-6

present the values used for the scenario modeled in the sensitivity run.

For the summer, the initial ($t = 0$) and boundary ($x = 0$, AB lagoon mouth) condition for FC concentration in the AB lagoon water column was set at 4E6 MPN/m^3, the recreational water quality standard for California beaches. The initial concentration for sediment FC was 10^5 MPN/kg (where the bulk density is assumed to be approximately 1400 kg/m^3). A difference of approximately 2 orders of magnitude between the sediment FC concentrations and the overlying water column is assumed because estuarine sediments contain concentrations of indicator organisms that are 1–3 orders of magnitude greater than those in the overlying water [24], and 3–4 orders of magnitude greater in storm drain sediments [42]. Ocean initial and boundary (nearest the lagoon mouth) conditions assumed a background FC concentration of 2E5 MPN/m^3 plus the initial lagoon FC concentration completely mixed in the first model subunit as calculated by Eq. (7).

For the simulation of winter conditions in the lagoon, we assumed a storm duration of 129,600 s (1.5 d) with the rising leg of the hypothetical hydrograph lasting 48,600 s based on the SCS hydrograph relationship of $T_r = 1.67T_p$ which relates recession time to rise time. The shape of the hydrograph is a linear rising and linear falling limb. From the USGS gauge data for AB creek during the years 1970–1993, the base flow in winter is approximately 0.3 m^3/s and the average annual peak flow is 4.6 m^3/s (Table 1). A sediment storage model was not included in the winter simulation because the sediments were assumed to be well-mixed vertically and their concentrations were not assumed to vary temporally during scouring events. The lagoon water initial and boundary FC concentrations were set at 3E8 MPN/m^3, a reasonable magnitude for AB Creek during storm flow conditions. The ocean initial and boundary FC concentrations were, as for the summer model, calculated by adding the loading from the creek to the background FC concentration resulting in a constant initial condition of 6E7 MPN/m^3 in the ocean. Because the lagoon discharge changes abruptly under the peak storm flow conditions, the boundary concentrations (concentrations in the ocean at the lagoon mouth) mimic the shape of the stormflow hydrograph.

We simulated FC concentrations in the lagoon, sediment and ocean for summer and winter seasonal conditions. We compared the results of these simulations to actual field data of FC concentrations in the ocean in the surf zone at the AB lagoon mouth. We then evaluated the sensitivity of our model to the boundary conditions and k_d, R_t, f, u_t and v_s values.

All programming and simulation was done in MATLAB 5 (The MathWorks Inc., Natick, MA), a numerical computation software package.

8. Results

8.1. Summer simulation

Net loss (combined death and settling) of FC in lagoon water dominates in the summer (Fig. 3). Because advection is so minimal for the dry flow conditions, the large residence time allows for the lagoon to act as a detention basin for creekwater prior to entering the ocean. Note that over 99% removal of FC from the lagoon water column is predicted (Fig. 3). However, by

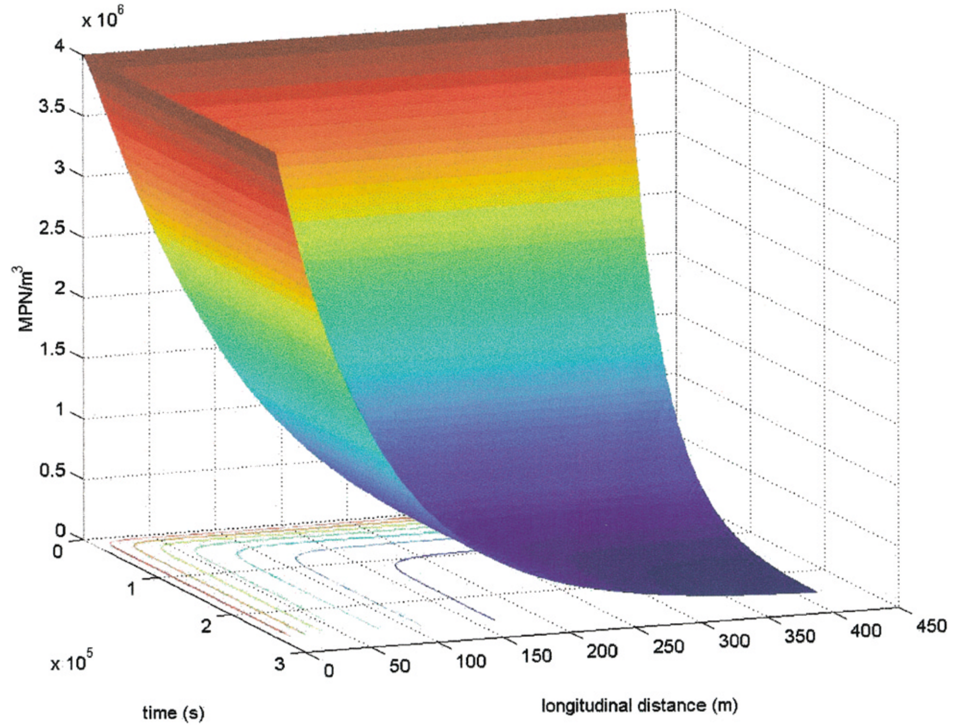

Fig. 3. Simulated FC concentration in AB lagoon water column during the summer. Note that $MPN/m^3 = (MPN/100\,ml) \times 10{,}000$.

comparing the magnitude of the death coefficient (k_d= 1.74E-5 s^{-1}) with the settling loss coefficient (v_s/H, or 5.78E-6 s^{-1}), it would appear that death dominates overall removal.

The lagoon sediment concentration is initially set at 10^5 MPN/kg because of prior reports that sediment concentrations may be at least 2 orders of magnitude higher than overlying water [42,24]. During the simulation, the model predicts an increase in the sediment FC of approximately 2 orders of magnitude (Fig. 4). As indicated by Fig. 4, the lagoon appears to function similarly to a clarifier in a wastewater treatment facility in that there is a critical distance, x_c beyond which there is no additional removal from the overlying water column. This distance can be calculated as: $x_c = u_t H/v_s$ and is the point at which all solids have settled out of solution. It occurs at approximately 305 m as evidenced by the sharp drop-off in the simulated sediment concentrations (Fig. 4). It can also be seen from Fig. 4 that sediment FC concentrations decrease with distance downstream. This phenomenon has been observed in limnetic environments previously [20]. Because the results of this simulation predict the average sediment FC concentration over the length of the lagoon is approximately 10^7 MPN/kg, this value was chosen to represent the average lagoon sediment FC concentration for the simulation of winter lagoon conditions.

Much like the lagoon water simulation, losses dominate in the ocean during the summer (Fig. 5). However, in this model, settling is not included because wave-induced mixing is assumed to increase shears beyond τ_c. Therefore, losses include only death and dispersion to outer, more offshore subunits in the y-direction. Because the offshore flux is proportional to the concentration gradient between the two subunits, losses due to this process are greatest initially where the loading from the lagoon is greatest. The scale of the z-axis of Fig. 5 should be noted; dilution is very significant because of the very low discharge from the lagoon relative to the size of the mixing zone in the ocean. Therefore, simulated changes in the ocean concentration from the background levels west of the lagoon mouth (i.e. upstream) would be virtually undetectable through standard enumeration methods.

By plotting lagoon water influent and effluent FC concentrations versus time one can clearly see that for a constant input of 4E6 MPN/m^3 at a flowrate of 0.017 m^3/s, greater than 2-log removal of FC is predicted to occur in the lagoon over a 70-h period (Fig. 6). Simulated effluent concentrations are nearly zero. Steady conditions are reached once the simulation time passes the residence time of the lagoon, which is approximately 2.38E5 s (67 h) for the summer

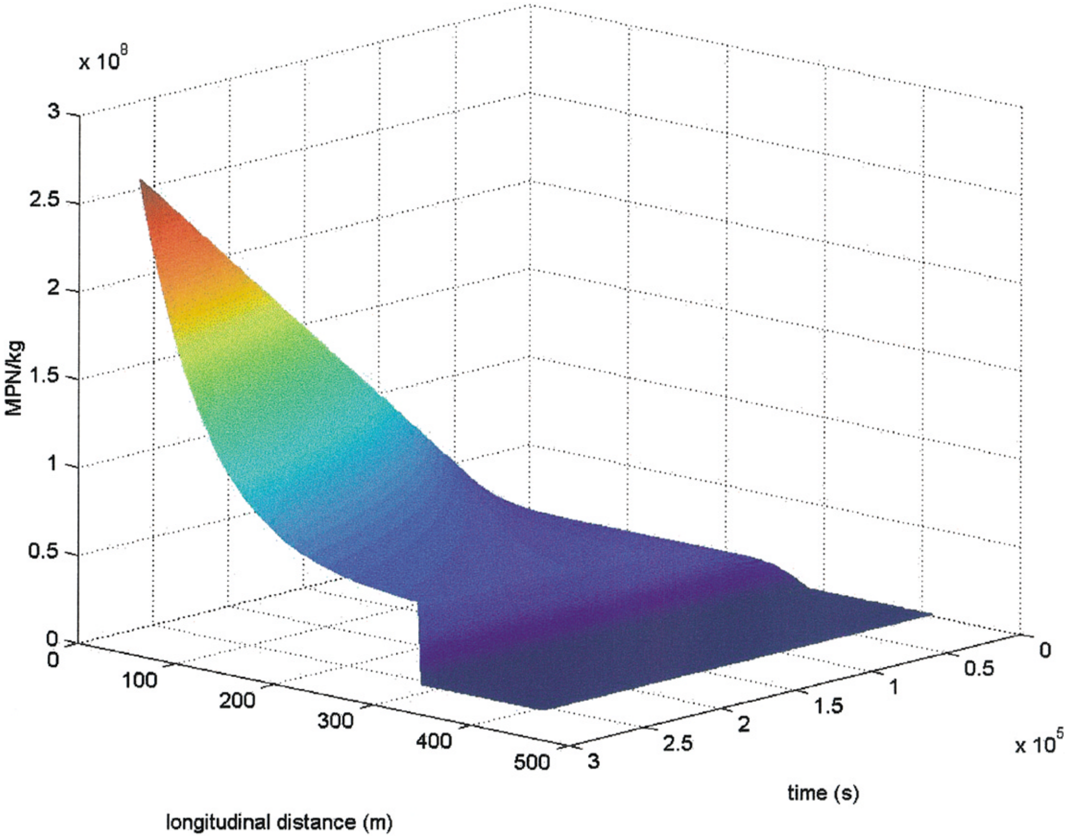

Fig. 4. Simulated FC concentration in AB lagoon sediments during the summer.

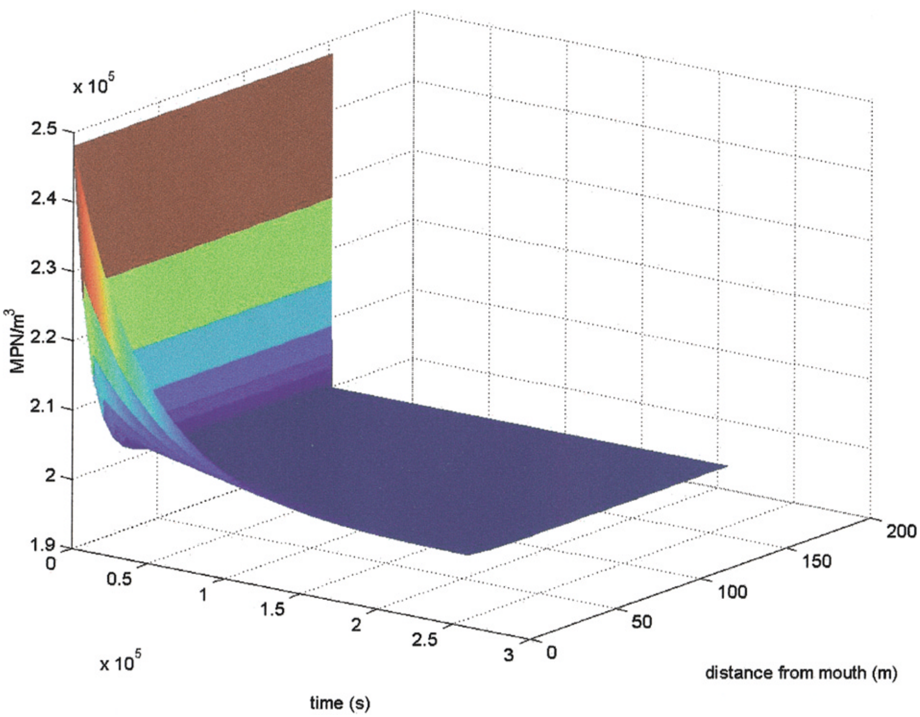

Fig. 5. Simulated ocean FC concentration during the summer. Note that $MPN/m^3 = (MPN/100\,ml) \times 10{,}000$.

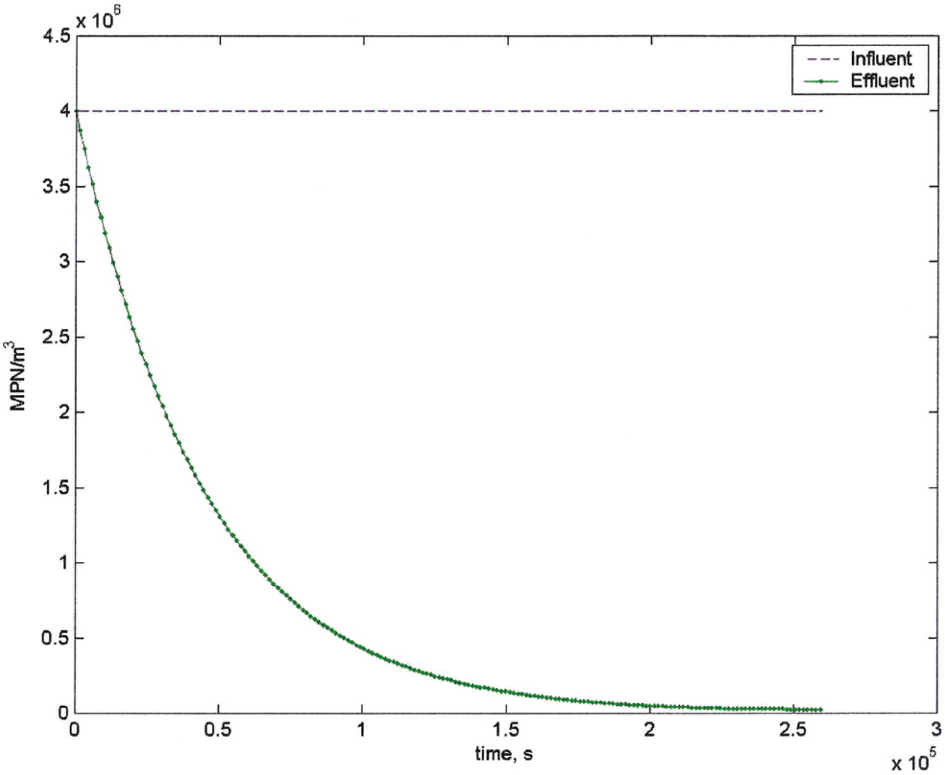

Fig. 6. FC removal from AB lagoon water over time. Note that $MPN/m^3 = (MPN/100\,ml) \times 10{,}000$.

conditions. A discussion of the validity of these results follows in the model verification section of this report.

8.2. Winter simulation

The results of the winter simulation for the lagoon and ocean waters are shown in Figs. 7 and 8. From Fig. 7 it can be seen that, once at a steady state, FC concentration increases linearly but gradually with distance downstream. Resuspension and advection processes dominate FC transport in the lagoon during the simulated storm event. In contrast to the summer model, the sediment bed is a source of FC to the water column. Wyer et al. [55] observed a rapid increase in FC and suspended solids concentrations with flows occurring during the rising limb of the hydrograph. There are two explanations: (1) resuspension is a strong function of velocity and (2) as per Wyer et al. [6], a negative correlation between FC concentrations in the sediment and bed depth, so that the most contaminated sediments should be resuspended shortly after flows exceed τ_c. In our winter simulation results, the sharp initial FC concentration increases are in agreement with Wyer et al.'s observations [6]. Additional explanations for the greater FC concentrations predicted by the winter model include the fact that death rates are less in the winter because of increased suspended sediment concentrations (resulting in much greater light attenuation through the water column), decreased incident solar irradiation, and decreased temperatures. Additionally, retention times within the lagoon are orders of magnitude less, allowing for significantly less die-off.

The results of the ocean simulation show a dramatic loss in FC concentrations immediately downstream of the lagoon mouth. The boundary condition is evident in the spike on the left side of Fig. 8. The simulation results show the ocean FC concentrations returning to background levels within 150 m east of the lagoon's mouth, even at the time of peak discharge. Within 60 m of the lagoon's mouth, these concentrations are over 3 orders of magnitude greater than they are for the summer ocean simulation.

Fig. 9 shows the results of the winter lagoon simulation. By observing this plot of influent and effluent concentrations versus time, it can clearly be seen that the role of the lagoon in the winter is that of amplifying creek FC concentrations, in this case by approximately 23%, before reaching the ocean. As the consolidated sediments are the only source of FC to the overlying water column, for the winter stormflow scenario that we

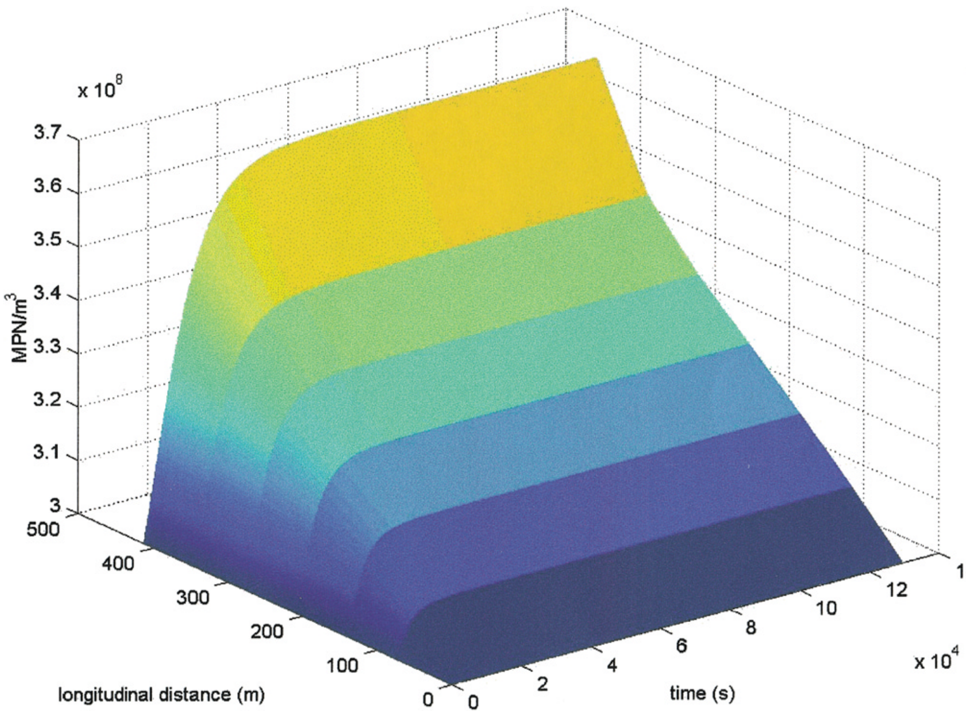

Fig. 7. Simulated FC concentration in AB lagoon water column in the winter season. Note that $MPN/m^3 = (MPN/100\,ml) \times 10{,}000$.

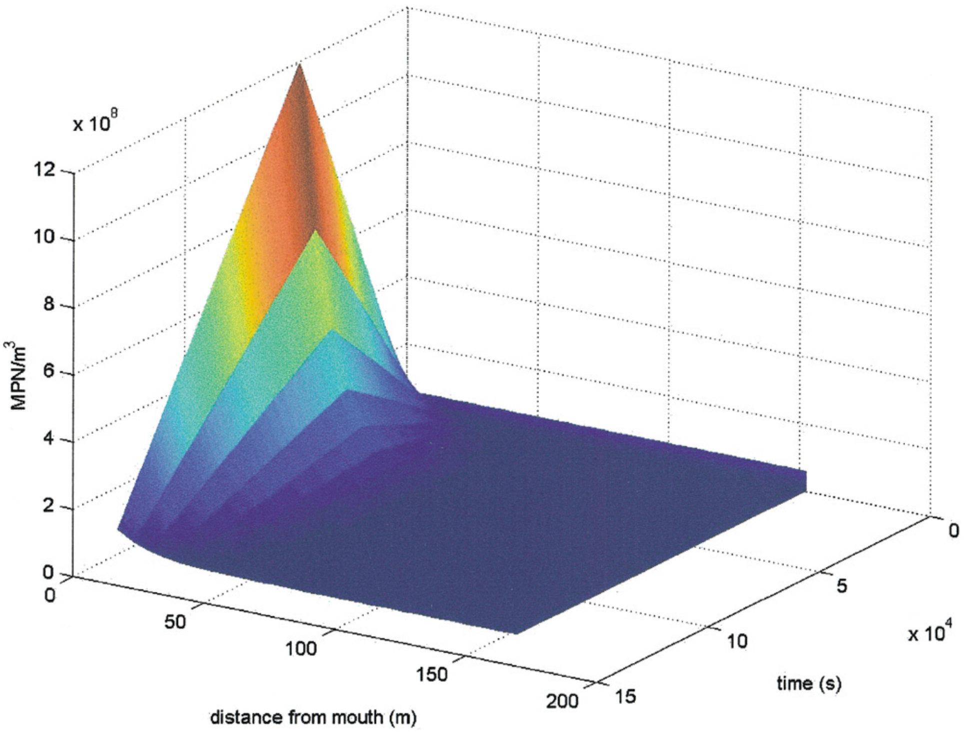

Fig. 8. Simulated FC concentration in ocean in the winter season. Note that $MPN/m^3 = (MPN/100\,ml) \times 10{,}000$.

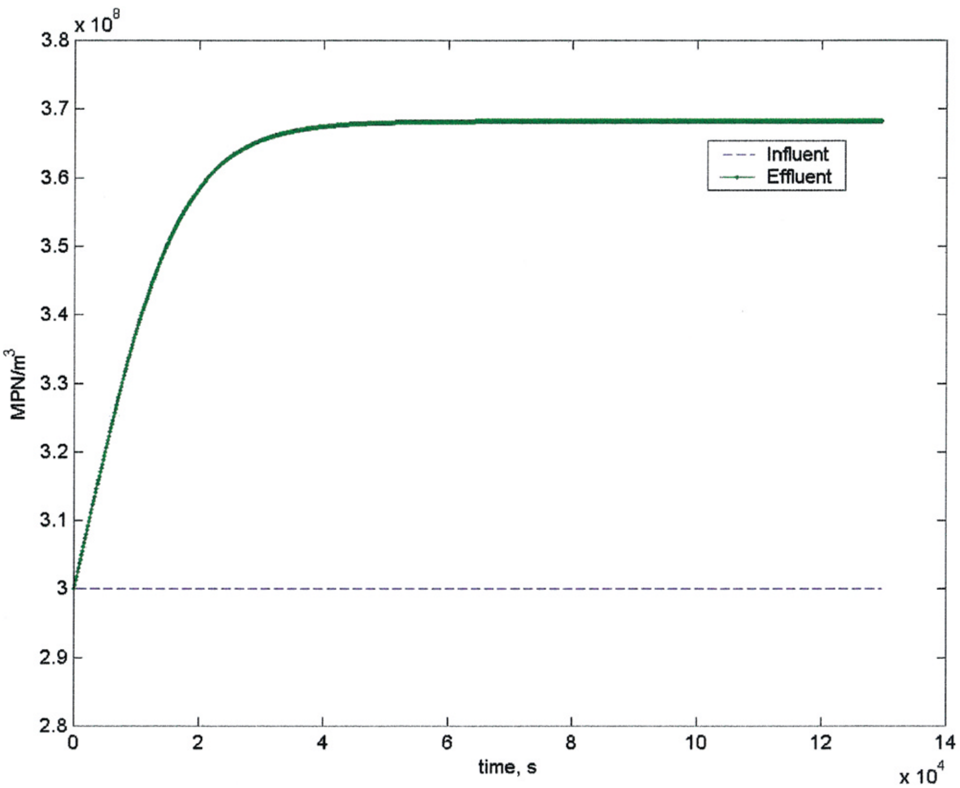

Fig. 9. Predicted lagoon water column FC concentration during the winter as a function of time. Note that MPN/m^3 = (MPN/100 ml) $\times$ 10,000.

simulated it can be said that resuspension dominates with the net effect of increased FC concentrations over the length of the lagoon. Noting the magnitude of the y-axis values, concentrations at the lagoon mouth are 3–4 orders of magnitude greater in the ocean for the winter simulation than for the summer. This is due to increased lagoon effluent concentrations and discharge rates, resulting in the combination of greater loading and less dilution.

9. Validation

In Fig. 10 two plots are shown of measured and modeled data versus distance downstream in the AB lagoon for both the summer and winter conditions. All measured data were taken by the Santa Barbara County Water Agency (http://www. sbcphd. org/ehs/ocean. htm). The field data was collected by the County using multiple tube fermentation with defined media according to standard methods for FC enumeration [56] applied to grab samples taken during several sampling campaigns during the years 1998–99. Three locations were sampled: AB Creek at the entrance to the lagoon, the AB lagoon 180 m upstream of the mouth, and the ocean at ankle depth immediately downstream of the lagoon mouth. In Fig 10, numerous simultaneous FC data for the AB creek, lagoon, and ocean are shown on log plots. Since this data is presented in log-linear form, the simulation results are re-presented in Fig. 10 for ready comparison to the field data. In comparing the field data to the summer condition simulation results (Fig. 10a), we see that the model predicts the FC concentration internal to the lagoon within an order of magnitude. There are several explanations for the differences between our model output and the actual field data. First, losses may be over-predicted because of an overestimated k value. Second, advective and/or dispersive transport through the lagoon could be underestimated (so that model residence times are overestimated) due to short-circuiting that may occur within the actual lagoon. The predicted ocean concentration (Fig. 10A), on the other hand, is within the range of reported field data.

The storm season data of Fig. 10B are for storm events of much smaller magnitude than the one simulated. For this reason, we anticipated that our simulation conditions would result in simulation FC values less than those observed in the field (Fig 10B). However, R_t and the boundary conditions for the AB

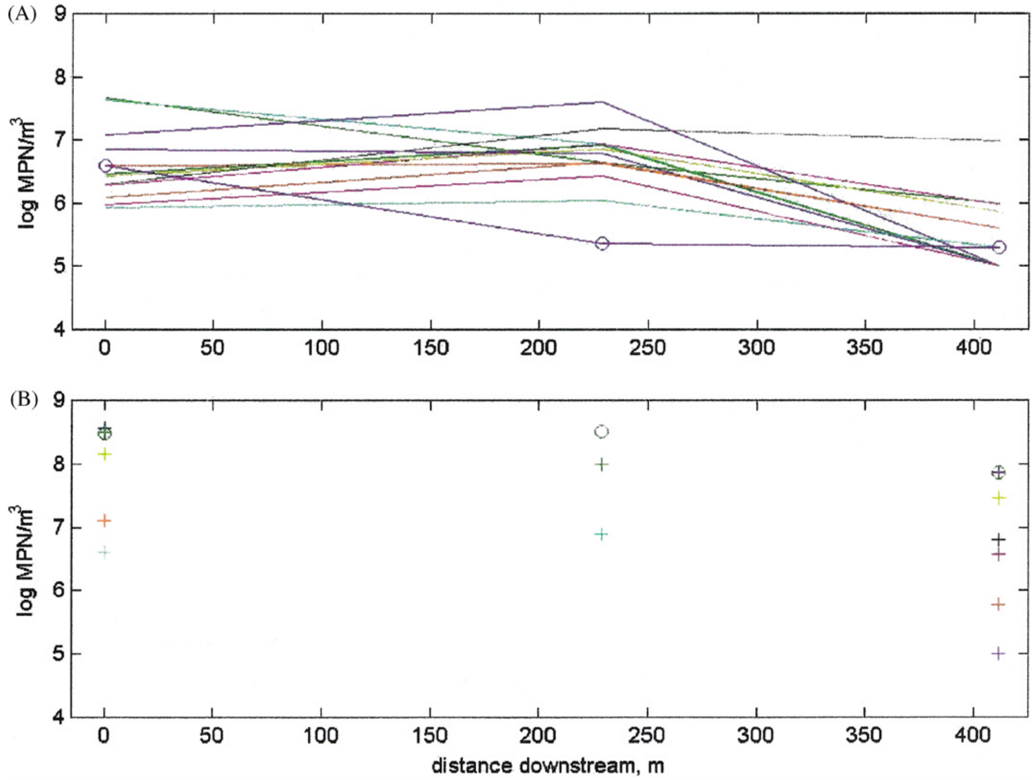

Fig. 10. Comparison of field measurements and predicted FC concentrations upstream of the AB lagoon, within the lagoon and downstream at the mouth where ocean mixing occurs. (A) Summer season, (B) winter season. Circles in A and B represent simulated data. Lines in A are continuous field data collected by Santa Barbara County on numerous occasions during dry season in 1998/99. Crossed-bars in B are color-coded for individual time points of field data collection in the winter of 1998/99. Note that MPN/m^3 = (MPN/100 ml) × 10,000.

lagoon water and sediments are expected to significantly influence model-based predictions and thus we recognize that model parameters can constrain the results to appear less predictive.

Fig. 11 provides a plot of modeled and measured ocean FC concentrations as a function of distance from the lagoon mouth. The measured data points were taken from the URS [12] ocean dispersal investigation, performed on March 26, 1999 when discharge from the AB lagoon was measured at 0.80 m^3/s. For comparison, results from modeling the ocean FC concentrations were extracted for the following time/flow conditions of our hypothetical hydrograph: 7200 s at 0.8 m^3/s, 48,600 s at 4.6 m^3/s, and 118,800 s, at 0.8 m^3/s. In the simulation shown in Fig. 11, the lagoon sediment resuspension rates were decreased from 0.0508 m over 129,600 s to 0.0254 m over 129,600 s, which is an adjustment that makes sense considering the slight over-predictions made by the winter lagoon model. Constant initial and boundary conditions for the lagoon model were assumed to be 3E7 MPN/m^3 and 1E6 MPN/kg for the lagoon water and sediments, respectively. Finally, dispersal in the y-direction was altered by adding a distinct dispersion coefficient for the y-direction, such that $E_y = 1.5\,m^2/s$. This has the effect of increasing dispersion in the offshore direction (which is a loss from the modeled shoreline subunits) relative to the dispersion in the direction of flow. This would make sense intuitively because the swashing, runup/rundown motion of waves is primarily in the y-direction (normal to the shoreline), and thus dispersion should be greater parallel to this motion.

It should be noted from Fig. 11 that the model results taken during the rising limb of the hydrograph match very well with measured ocean concentrations. However, because of increased lagoon water concentrations due to resuspension occurring over the course of the simulation, the results taken during the recession of the hydrograph are over an order of magnitude too great. The results are also shown for model predictions during the peak discharge for comparison. As should be the case, these values vastly over-predict the measured concentrations. It should be noted that the near perfect match of the model prediction during the hydrograph

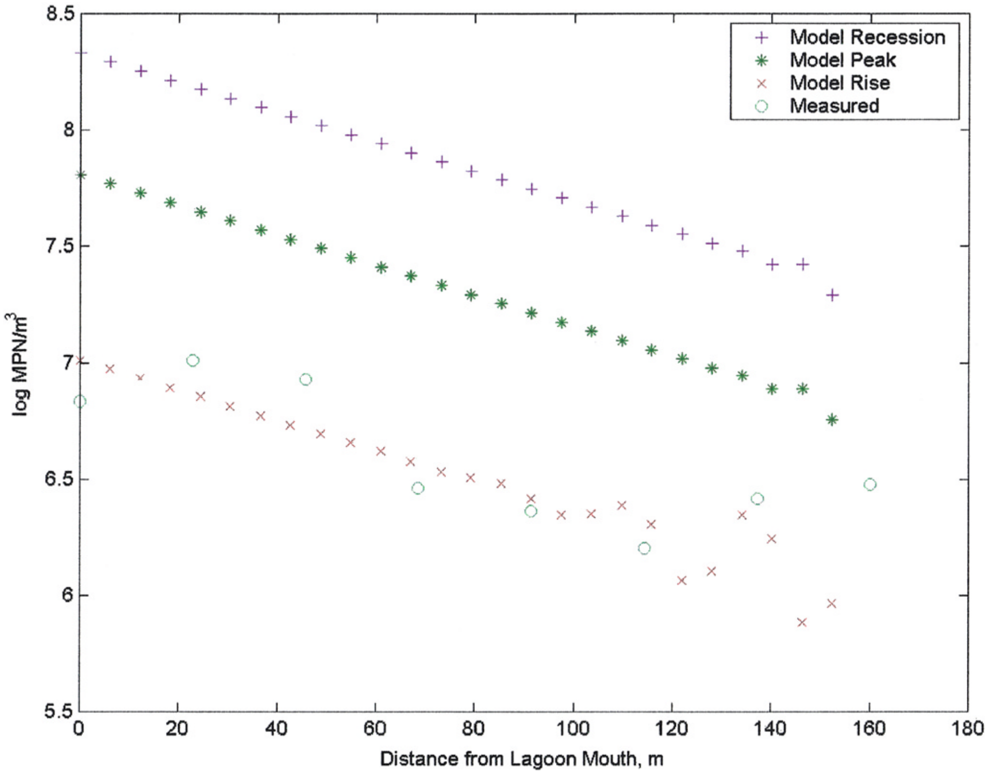

Fig. 11. Comparison of predicted ocean water FC concentrations with measured concentrations in the AB surf zone. Note that MPN/m^3 = (MPN/100 ml) × 10,000.

rise towards the downstream end of the simulation results is a result of constraining the model to increase the dispersion in the y-direction.

10. Sensitivity analysis

Figs. 12 and 13 present the results of the sensitivity analyses. By plotting lagoon effluent concentration curves versus time for different modeling scenarios, the sensitivity of results to various changes in parameter values can be noted. From Fig. 12 it should be noted that the summer model is not particularly sensitive to any of the parameter ranges simulated. As anticipated, higher decay (i.e. greater death coefficient and settling velocity) results in faster loss response through the lagoon. The 50% flow short-circuiting and the 10 × pulse increase in entrance concentration each have negligible effects on effluent lagoon concentrations. Therefore, the under-predictions resulting from our simulating summer lagoon FC concentrations are likely due to errors in k estimates, as k is the most sensitive parameter for this seasonal condition.

Fig. 13 shows the sensitivity of the winter model to resuspension and decay scenarios. As expected, greater resuspension rates and lower death coefficients result in increased lagoon effluent concentrations. Considering the range in parameter values anticipated for the lagoon, it seems that the winter model is more highly sensitive to resuspension values than it is to decay values. Therefore, any under-predictions occurring with the simulation of winter FC concentrations are likely due to error in estimating R_t. Finally, it should be noted that whereas the summer lagoon simulation results show orders of magnitude changes in effluent concentrations over time, the winter simulation results experience less dramatic changes in concentration.

11. Conclusions

One of the few coastal lagoon pathogen studies conducted is by Gersberg et al. [11] in which the effect of breaching the sand berm—which had previously separated the lagoon from the ocean—on ocean water quality was observed. It was then demonstrated that ocean water quality was poorest subsequent to opening the lagoon mouth. However, whether the lagoon served to, under normal seasonal conditions, amplify or attenuate upstream (creek) sources of biological

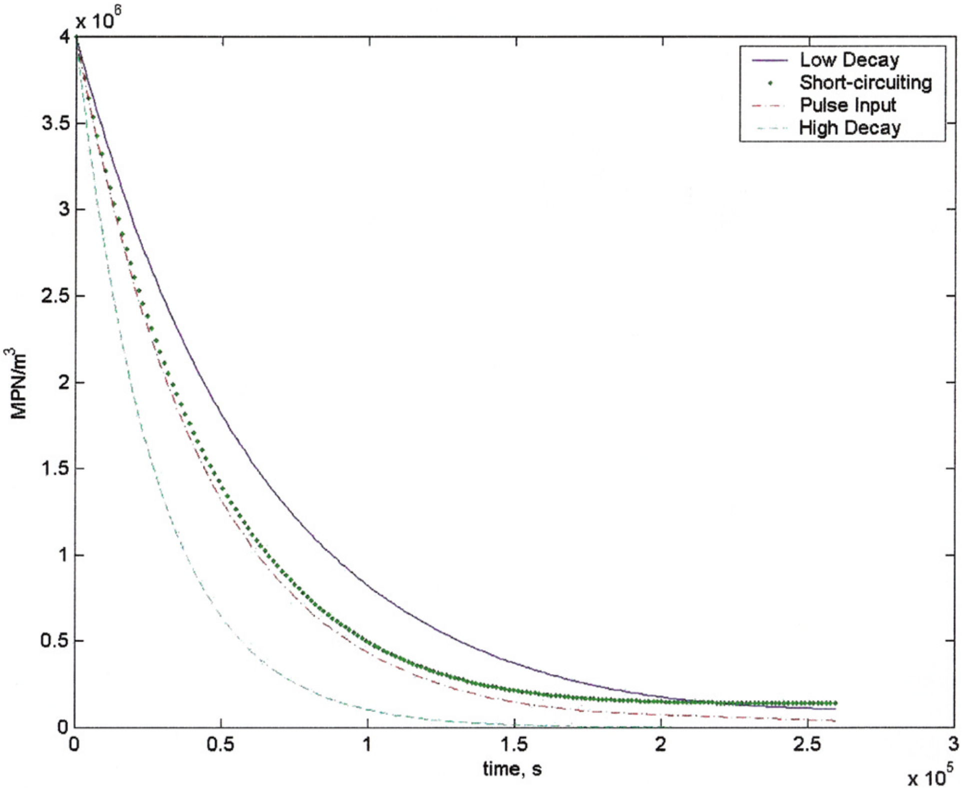

Fig. 12. Sensitivity of summer season model of FC concentrations in the AB lagoon water column to variations in FC removal rate and flow characteristics. Note that $MPN/m^3 = (MPN/100\,ml) \times 10{,}000$.

contamination prior to ocean discharge was not determined. Our modeling suggests that the lagoon serves a seasonally varying function with regards to coastal FC concentrations that originate in upstream urban creeks. On one hand, the lagoon attenuates creek FC through net loss in the summer; on the other hand, FC-laden sediments are released to the ocean during high storm flow conditions in the winter. While it is already known that bottom sediments are an extremely significant source of pathogens to the overlying water column [50,55,57] our model suggests when coastal water quality managers should be most concerned about this fact. This concern for the mixed role of the coastal lagoon is consistent with a recent study of a California coastal marsh where marsh processes were implicated in negatively impacting coastal bacteriological water quality [8]. However, our ocean model results from two extreme hydrologic conditions suggest that the release of lagoon FC has a short-range impact on ocean water quality due to the dominance of dilution and bacterial die-off in the marine environment.

The validity of our model should be tested further by comparing simulations to other field data sets and by further confirmation of the parameter values that we assumed for our simulations. Of the many parameters required by the model, perhaps the least predictable, most widely variable, and most influential to the models are bacterial decay, turbulent dispersion, and sediment resuspension rates. In situ measurements of these lagoon parameters are required before this model can be made sufficiently reliable. Finally, we did not consider bacterial re-growth in the lagoon sediments nor sources other than bottom sediments. However, the possibility of FC amplification in sediments and alongshore should be investigated and perhaps incorporated into our model framework because of a recent report that *E. coli* are capable of growth in natural intertidal subtropical sediments and erodable river banks [58].

In summary, the mechanistically based models presented here could be useful for describing the fate of FC in creek water as it passes through a coastal lagoon and the effects of lagoon discharge on bacteriologic water quality in the surf zone. Our results suggest that, during summer baseflow conditions in the creek, bacterial die-off dominates, while during winter stormflow conditions resuspension of highly concentrated sediments in the lagoon dominates. These results are similar to field conditions for a reference site and are consistent with previous published reports. This study provides additional insight into the lagoon's role as a distinct

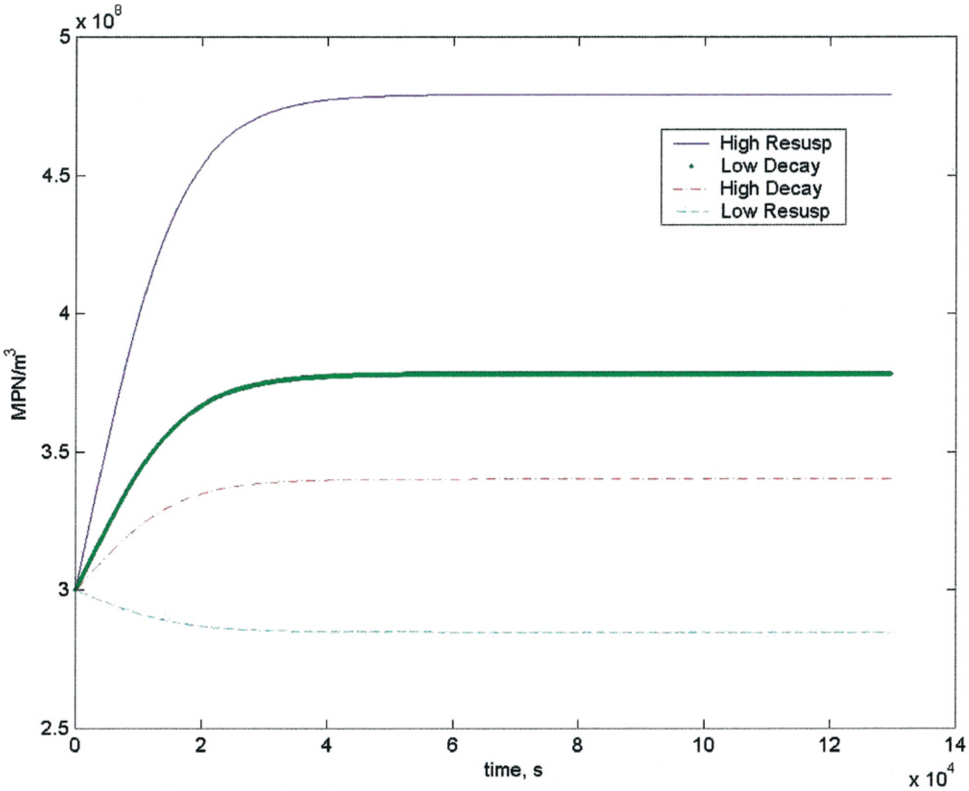

Fig. 13. Sensitivity of winter season model of FC concentrations in the AB lagoon water column to variations in FC resuspension rate and FC death rate. Note that $MPN/m^3 = (MPN/100\,ml) \times 10{,}000$.

compartment of the coastal watershed in the fate and transport of fecal contamination towards the coast. In addition, the model and resulting simulations could serve as a tool for coastal water quality management given acquisition of site-specific parameters.

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